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Incremental design of control system of SHARON-Anammox process for autotrophic nitrogen removal

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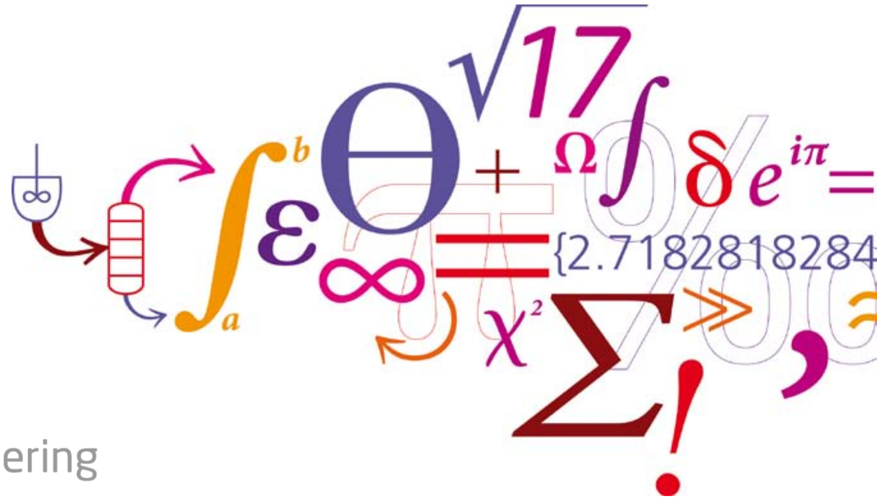


Introduction and motivation

The design of the control structure of a bioreactor is challenging due to:

- Plant and model complexity with different time scales and large interactions
- Lack of actuators/control degrees of freedom to act upon the process
- Narrow operation window (in particular pH, temperature and concentration of substrate/product)
- Model mismatch due to lack of knowledge about the microorganism metabolism
- Adaptation of the microorganisms during operation

We illustrate all these challenges in the design of a control structure for a process of nitrogen removal in wastewater treatment

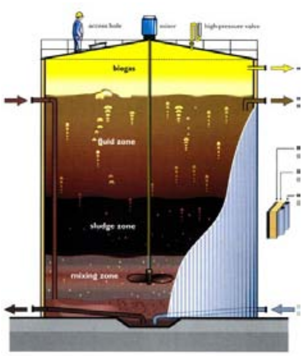
Overview of the presentation

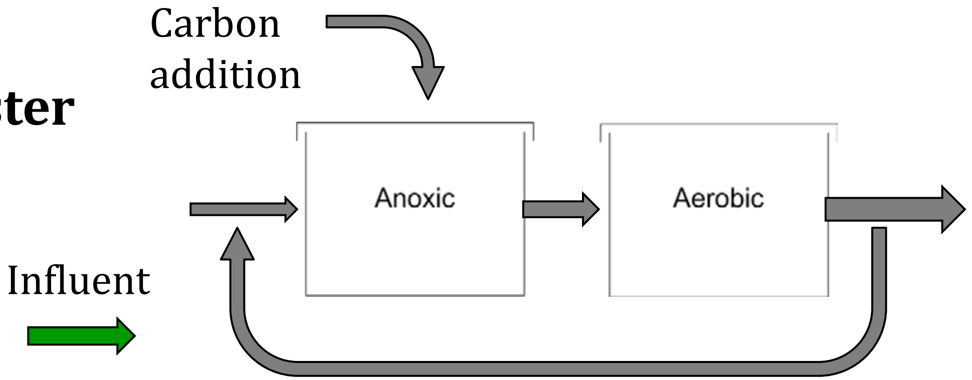
1) Why autotrophic nitrogen removal?
2) Modelling of the plant
3) Control design. Top-down analysis
4) Control design. Bottom-up design
   i. Closed loops disturbance gain
   ii. H_∞ controller
5) Evaluation
6) Conclusions

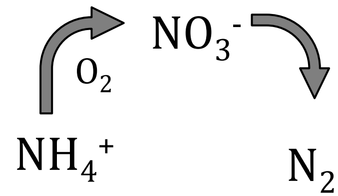
Why autotrophic nitrogen removal?

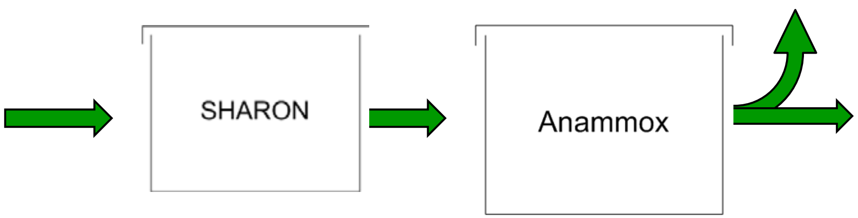
Nitrification/denitrification

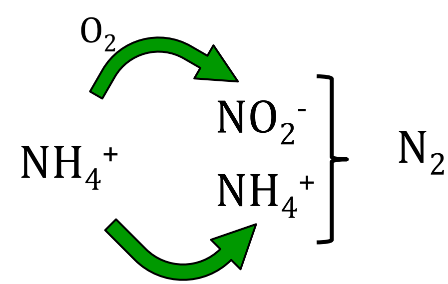
Anaerobic digester











Autotrophic nitrogen removal

- Less aeration and energy

- No need of carbon addition

- Lower footprint and sludge production

Model

Dynamic mass and charge balances. 13 ODEs per reactor

$$\frac{dV}{dt} = \sum_{n=1}^{i} F_{in}^{i} - F_{out}$$

$$\frac{d(V \cdot C_i)}{dt} = F_{in,net} \cdot C_{i,in,net} - F_{out} \cdot C_i + k_L a_i \cdot \left(C_i^* - C_i\right) \cdot V + r_i \cdot V$$

$$\frac{d(V \cdot Z^+)}{dt} = F_{in} \cdot Z_{in}^+ + F_{acid} \cdot C_{acid} + F_{base} \cdot C_{base} - F_{out} \cdot Z^+$$

Components:

8 compounds

4 microorganism types

charge

Determination of pH. 11 AEs per reactor

$$0 = TNH - \left(NH_4^+ + NH_3\right)$$

Mass balances (4)

$$0 = K_{e,NH4} \cdot NH_4^+ - NH_3 \cdot H^+$$

Equilibrium relations (6)

$$0 = Z^+ - NO_3^- - HCO_3^- - 2 \cdot CO_3^{2-} - H_2PO_4^- - 2 \cdot HPO_4^{2-} NO_2^- - OH^- + NH_4^+ + H^+$$

Charge balance

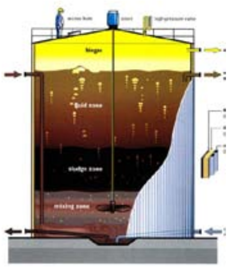
Microbial kinetics

r_i 11 processes considered

Vangsgaard et al. 1994

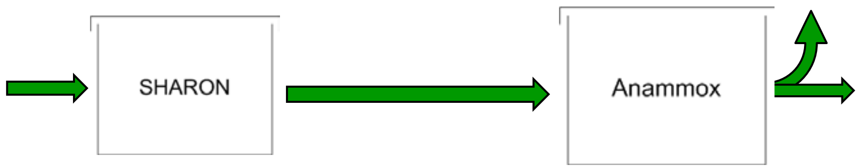
Control design. Top-down analysis

Control objectives



Faster growth ~1 d

Slow growth ~11 d



removal of >80 % of N load

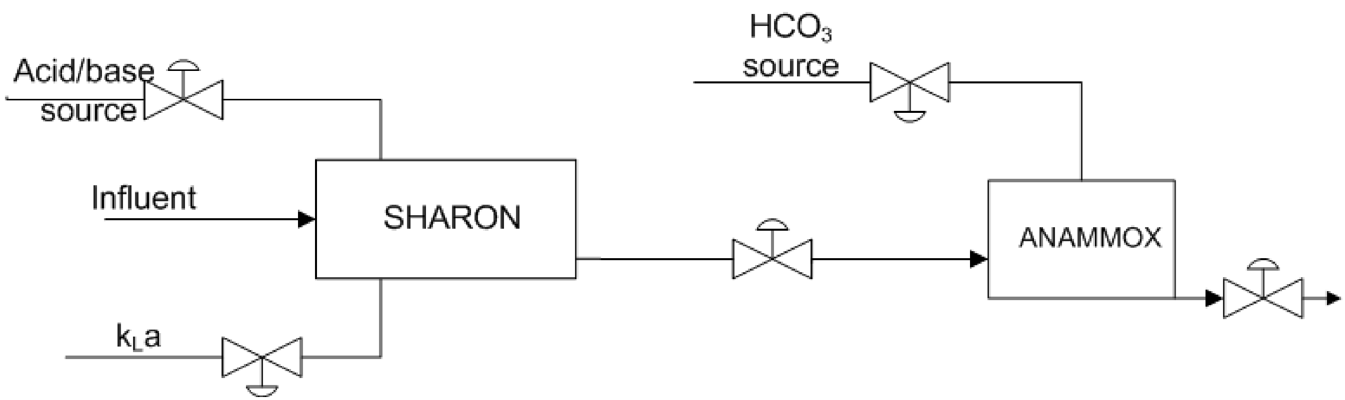
Influent

$TNO_2/TNH = 1.3$

$TNH = 700\ gN/m^3$

Use the SHARON reactor to dampen the disturbances

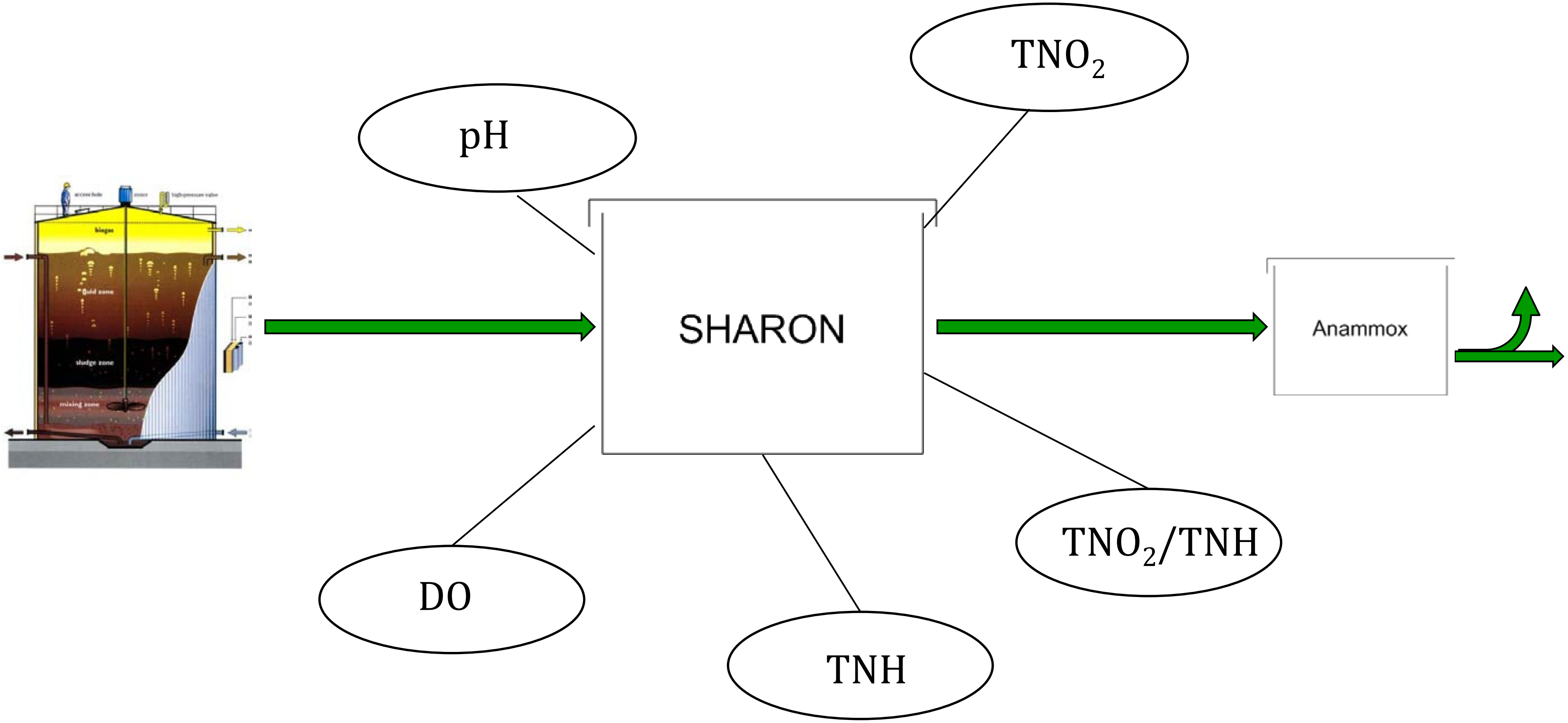
Control degrees of freedom (3)



How to link the controlled variables with the control objectives?

Control design. Top-down analysis

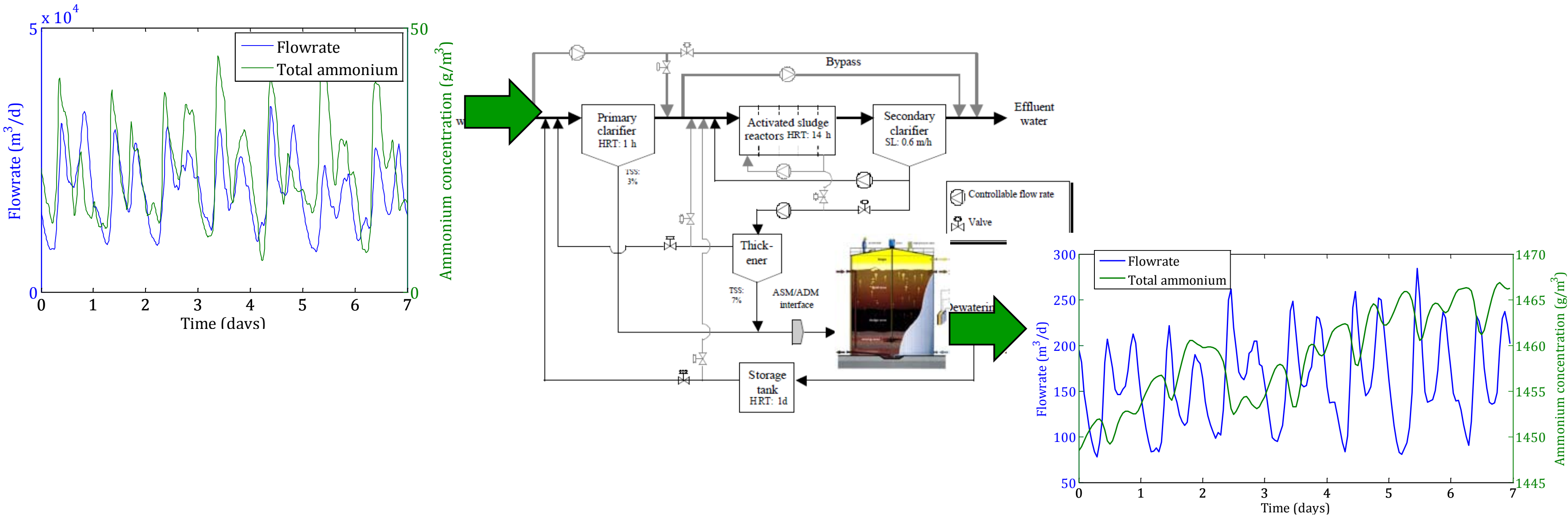
Potential controlled variables in SHARON



Conflict between regulation and the control objectives

Control design. Bottom-up synthesis

Selection of controlled variables



Closed Loop Disturbance Gain (CLDG)

$$CDLG = \tilde{G}_{(s)} G^{-1}{}_{(s)} G_d{}_{(s)}$$

CLDG = $|\delta_i| < 1$

The disturbance effect is lower than Δy_{max}

CLDG = $|\delta_i| > 1$

The disturbance effect is higher than Δy_{max}

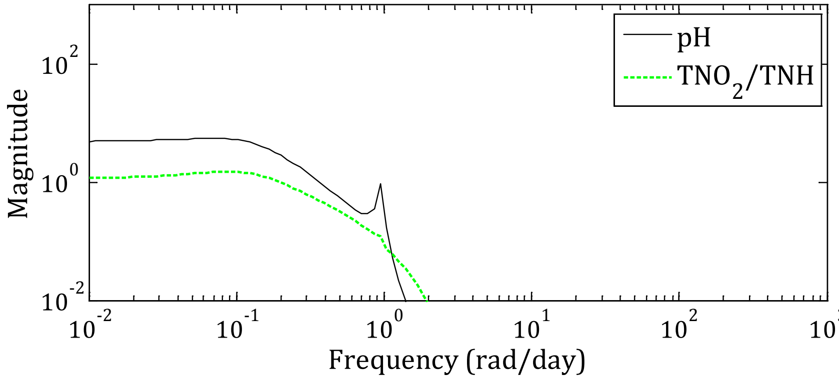
Need of control action!

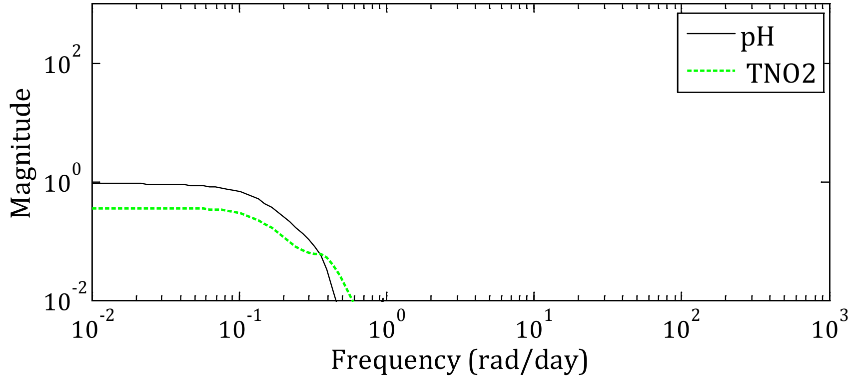
Hovd and Skogestad 1994

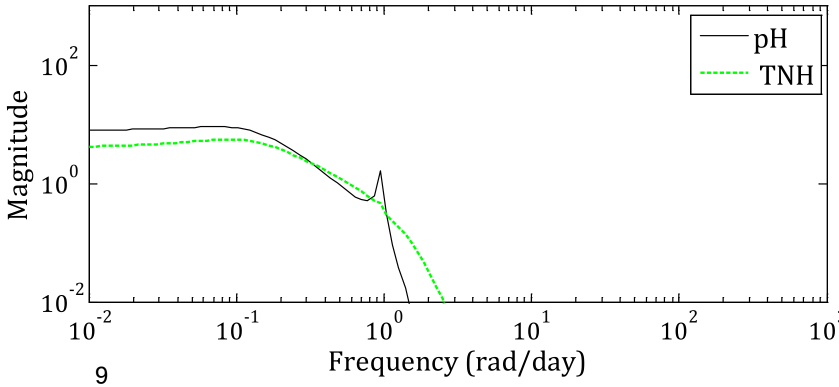
Control design. Bottom-up synthesis

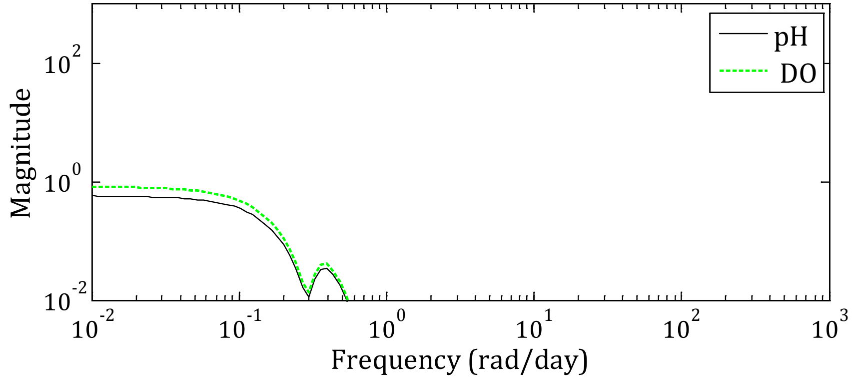
Variables	
pH	DO
pH	TNH
pH	TNO_2
pH	TNO_2/TNH
DO	TNO_2/TNH

Variables	
TNO_2	TNO_2/TNH
TNH	DO
TNH	TNO_2
TNO_2	DO
TNH	TNO_2/TNH









Control design. Bottom-up synthesis

Selection of controlled variables

Other requirements

$$S=\frac{I}{I+G(s)C(s)}$$ has to be bounded for performance

$$T=\frac{G(s)C(s)}{I+G(s)C(s)}$$ has to be bounded for robustness and to avoid sensitivity to noise

$$C\,S=\frac{C(s)}{I+G(s)C(s)}$$ has to be bounded to penalize large inputs

$$\min_{C}\ \left\|N(C)\right\|_{\infty} \qquad N \,\square \begin{pmatrix} W_U C\,S \\ W_T T \\ W_P S \end{pmatrix}$$

stacked optimal H_{∞} problem

$$\bar{\sigma}\big(CS(j\omega)\big) \le \gamma\, \underline{\sigma}\big(W_u^{-1}(j\omega)\big)$$

$$\bar{\sigma}\big(T(j\omega)\big) \le \gamma\, \underline{\sigma}\big(W_T^{-1}(j\omega)\big)$$

$$\bar{\sigma}\big(S(j\omega)\big) \le \gamma\, \underline{\sigma}\big(W_P^{-1}(j\omega)\big)$$

γ must be small to ensure good controllability

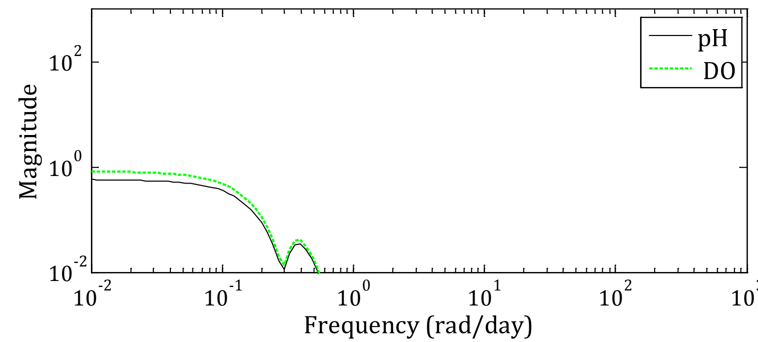
Skogestad, S. and Postlethwaite, I. (2005)
Jahanshahi, E. and Skogestad, S. (2012)

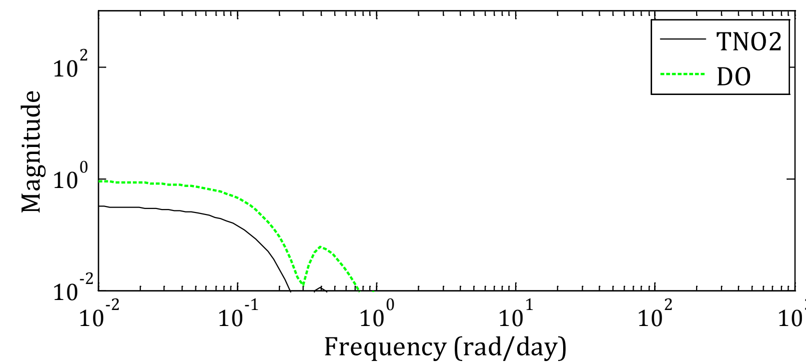
Control design. Bottom-up synthesis

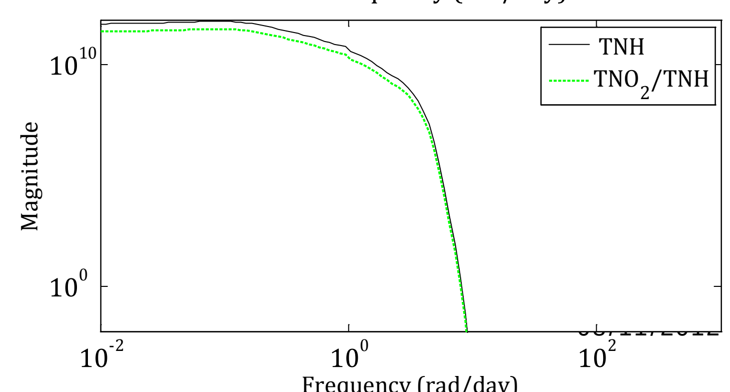
Selection of controlled variables

Ranking

Variables		**γ**
pH	DO	**13.1**
pH	TNH	**48.8**
pH	TNO_2	**58.6**
pH	TNO_2/TNH	**94.3**
DO	TNO_2/TNH	**100**
TNO_2	TNO_2/TNH	**100**
TNH	DO	**101**
TNH	TNO_2	**101**
TNO_2	DO	**inf**
TNH	TNO_2/TNH	**inf**

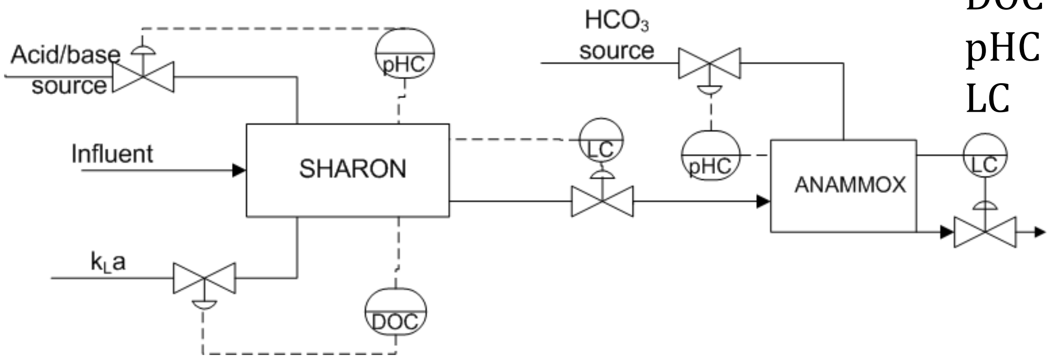






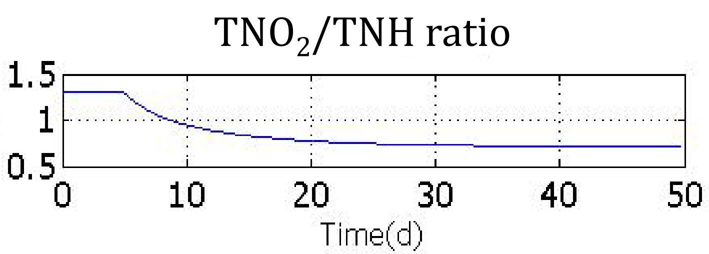
Control design. Bottom-up synthesis

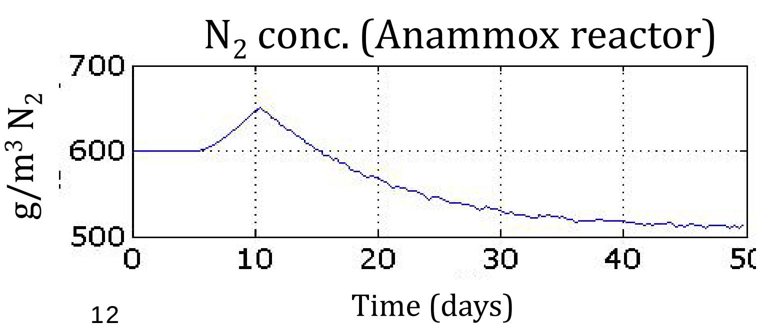
Regulatory layer



DOC = DO Controller
pHC = pH Controller
LC = Level Controller

Reponse to +5% step input in inflow





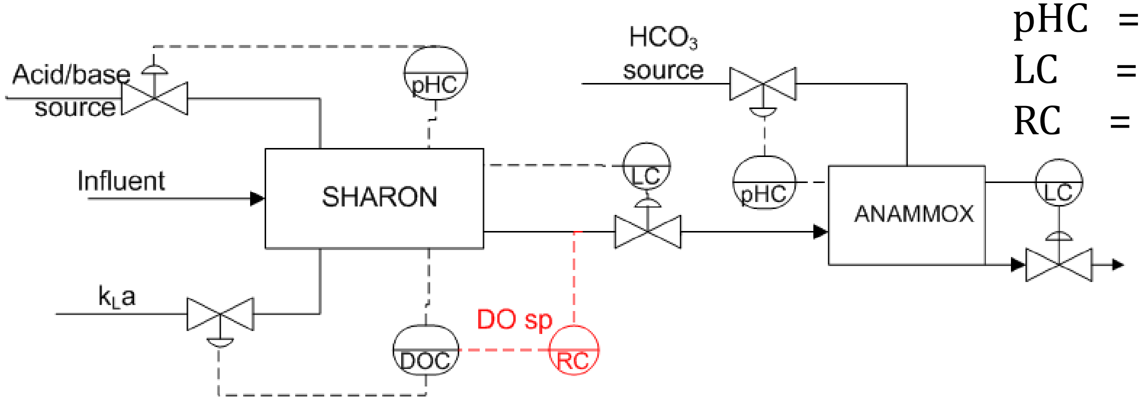
Good regulation

Need of master loop to correct the TNO2/TNH ratio

Control design. Bottom-up synthesis

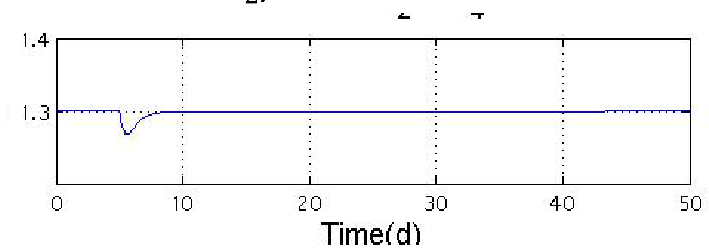
Supervisory layer

DOC = DO Controller
pHC = pH Controller
LC = Level Controller
RC = TNO_2/TNH Controller

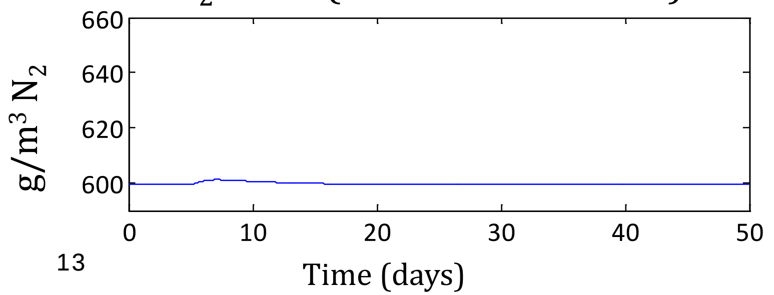


Reponse to +5% step input in inflow

TNO_2/TNH ratio



N_2 conc. (Anammox reactor)



The TNO2/TNH ratio is kept at the optimal value

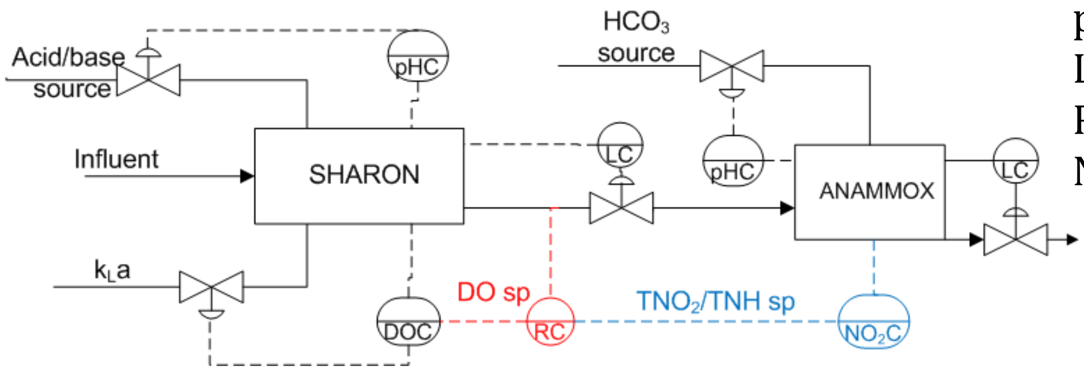
Model mismatch

Ammonium oxidation due to washed bacteria

Need of feedback from Anammox reactor

Control design. Bottom-up synthesis

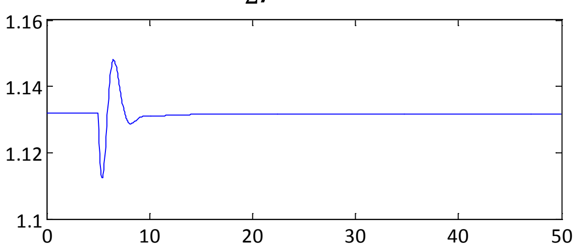
Supervisory layer



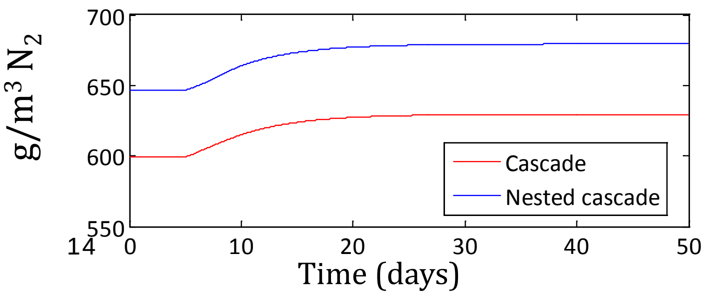
DOC = DO Controller
pHC = pH Controller
LC = Level Controller
RC = TNO_2/TNH Controller
NO_2C = NO_2 Controller

Reponse to +5% step input in TNH input

TNO_2/TNH ratio



N_2 conc. (Anammox reactor)



The amount of N_2 produced is maximized

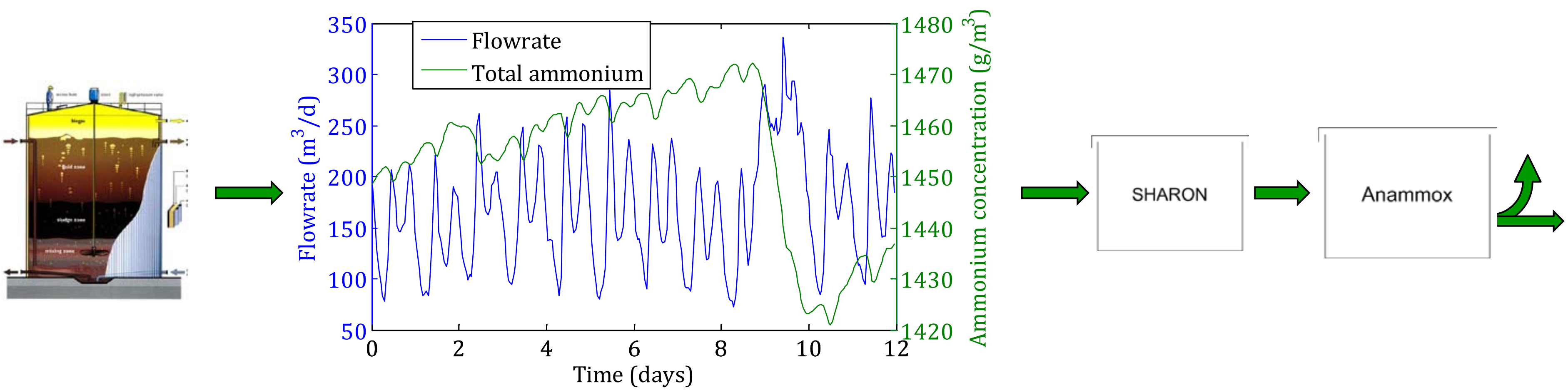
The cascade takes advantage of the time-scale separation of the reactors

Adaptation of microorganisms can be tackled

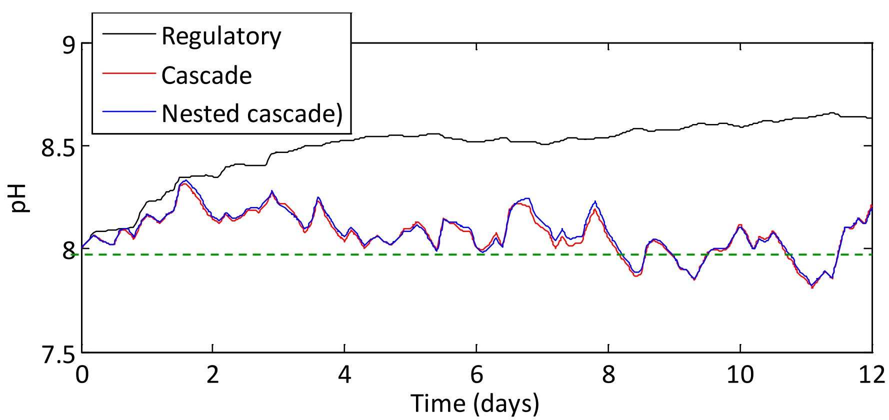
More complex structure

Evaluation. Dynamic simulation

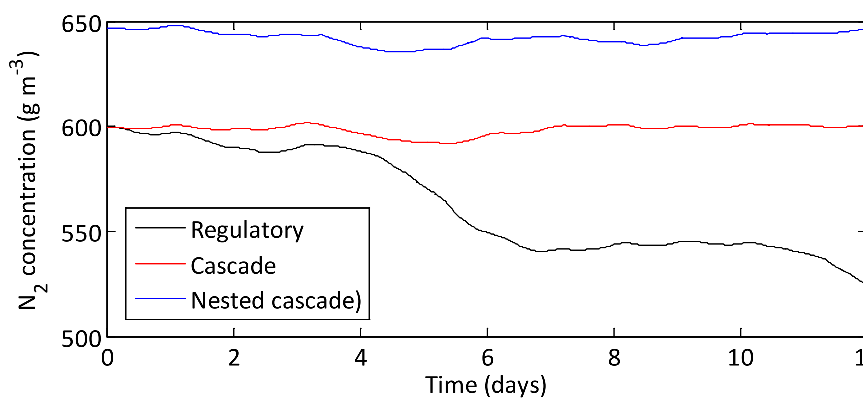
Benchmark simulation model 2 effluent



pH regulation (Anammox)



Nitrogen production (Anammox)



Evaluation. Results

$$IAE = \int_0^{\infty} \left| y^{SP} - y \right| dt \qquad TV = \sum_{i=0}^{n} \left| u_{i+1} - u_i \right|$$

Structure	Nitrogen removal		DO SHARON	pH SHARON	pH Anammox
Regulatory	**83.1%**	IAE	0.53 d	57.3 d	40.4 d
		TV	908 d^{-1}	$5.40 \cdot 10^{-4}$ $m^3 d^{-1}$	$1.60 \cdot 10^{-5}$ $m^3 d^{-1}$
Cascade	**88.9%**	IAE	6.22 d	60.0 d	29.2 d
		TV	$9.51 \cdot 10^3$ d^{-1}	$2.90 \cdot 10^{-4}$ m^3 d^{-1}	$2.00 \cdot 10^{-5}$ m^3 d^{-1}
Nested cascade	**95.6%**	IAE	7.23 d	60.0 d	29.3 d
		TV	$5.50 \cdot 10^3$ d^{-1}	$1.90 \cdot 10^{-4}$ m^3 d^{-1}	$1.90 \cdot 10^{-5}$ m^3 d^{-1}

Conclusions

Due to the lack of actuators, **selection of controlled variables** is challenging in bioreactors

We used two methods to select the controlled variables:

- the Closed Loop Disturbance Gain, emphasizing **the effect of disturbance rejection**

- **a trade-off between performance and robustness**, through the synthesis of a H_∞ controller

The regulatory layer was improved in order to address the process objectives, thereby producing designs of increasing complexity which can be adapted to the user's needs

Incremental design of control system of SHARON-Anammox process for autotrophic nitrogen removal

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